ARMY RESEARCH LABORATORY

Evaluation of ABB Fast Discharge A-Z Switch

Hardev Singh
Charles R. Hummer

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Aberdeen Proving Ground, MD 21005-5066

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Charles R. Hummer
Weapons & Materials Research Directorate

Abstract

The semiconductor switch 5SPY 36L4502 manufactured by ABB[1] has the capability of conducting current pulses with an amplitude of 150 kA and a width of 50 μs. This capability was achieved by a silicon wafer that is 91 mm in diameter. In addition, this switch can withstand a current pulse that is initially increasing at a rate of 10 kA/μs. This capability was achieved by a special triggering unit that produces a 9.5-kA pulse with a rise time of 2.5 μs, a low inductance structure between the triggering unit and the internal contact to the gate structure on the silicon wafer, and a highly inter-digitated gate structure. These capabilities make it possible to replace some spark-gap switches, thyratrons, or ignitrons used in research at the U.S. Army Research Laboratory with this semiconductor switch that is smaller, more reliable, and has a longer life time. Because of the possible uses for this switch, its characteristics were evaluated and the requirements for its use were determined. This study should assist in the design of new circuits and should determine if this switch could replace existing switches.

[1]Not an acronym

ACKNOWLEDGMENTS

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EVALUATION OF ABB[1] FAST DISCHARGE A-Z SWITCH

1. Introduction

The Weapons and Materials Research Directorate of the U.S. Army Research Laboratory (ARL) has a number of projects that require high power pulses. The power requirements of these projects are unique: high peak current (>100 kA), high voltage (>10 kV), and fast current rise rates (>10 kA/μs) at the same time. Because commercial applications do not need this combination of performance requirements even in a limited volume, manufacturers do not have the test equipment to evaluate the switches for military applications, and some important information cannot be obtained from the specifications issued by the manufacturer. Therefore, ARL has engaged in the evaluation of available high power switches.

A major problem with the silicon solid state thyristor is the difficulty of achieving fast current spreading across the semiconductor area at the initiation of current conduction. The current-spreading problem makes it difficult to use the total semiconductor area and thus makes it difficult to improve the current-carrying capabilities just by increasing the active semiconductor area. In order to increase the peak current, action, and dI/dt capabilities, an improved method of increasing current spreading must be developed. The dI/dt capability of the A-Z switch was the highest of any known commercially available silicon thyristor of its size. It was speculated that ABB Semiconductors AG, Lenzberg, Switzerland, may have developed an unique method to spread the current across the wafer. Thus, these switches were chosen for evaluation.

2. Device Construction

The devices that were evaluated resulted in a collaboration between ABB and the French-German Research Institute of Saint-Louis, Saint-Louis, Cedex, France, to replace spark gap switches used in electromagnetic launchers with solid state switches. This effort resulted in the development of the model 5SPY 36L4502 thyristor and a triggering unit to be used with the thyristor. In addition, a high current diode 5SDF 16L4502 was designed with a fast recovery to protect the thyristor from either an excessive forward voltage or a reverse current, depending on its placement with the thyristor.

[1]Not an acronym

The construction of the model 5SDF 16L4502 fast recovery diode is similar to other high power diodes. Both sides of the 91-mm diameter silicon wafer are silver coated and have no other features. The silicon wafer has a thickness of 0.58 mm. Contacts with the wafer are made by two molybdenum disks, each having a diameter of 83 mm and a thickness of 2.54 mm. One disk makes contact with the anode surface and the other disk makes contact with the cathode surface. The molybdenum disks and the wafer are between two copper disks whose tapered edges are bonded to a ceramic tube. Both copper disks have a diameter of 80 mm and a thickness of 10 mm.

The model 5SPY 36L4502 thyristor has a ceramic package that insulates the anode, gate, and cathode electrodes. The gate electrode is not a simple tab as usually found on other thyristor designs but is a complete ring, as shown in Figure 1. The gate electrode has 16 evenly spaced bolt holes near the rim to form a uniform contact with the printed circuit board of the triggering circuit. This geometry greatly reduces the inductance between the gate and the triggering circuit. Contact between the gate electrode and the gate ring is made by 12 radial pins that are insulated by plastic sleeves and fit into radial grooves of the cathode electrode.

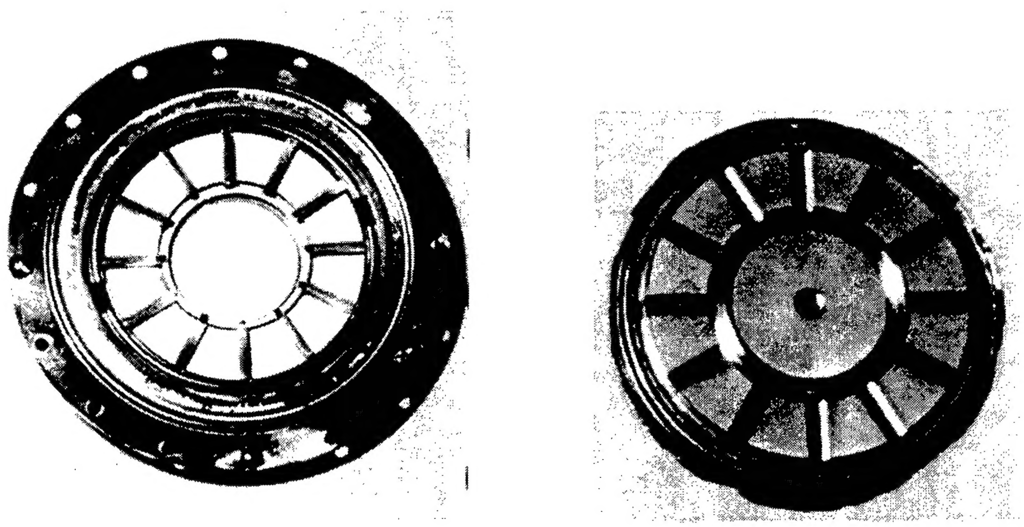

Figure 1. View of the Package After the Cathode Electrode (shown to the right) has been Removed.

Figure 2 is a cross-sectional representation of the molybdenum pieces that are in contact with the wafer and the plastic retainer ring. The dimensions in Figure 2 are not to scale. The anode disk is also in contact with the anode electrode of the package. The center disk and the outer ring are also in contact with the cathode electrode of the package. Thus, these molybdenum pieces conduct the main current through the thyristor. A plastic retainer ring contains a spring arrangement that presses the radial pins onto the gate ring and insulates the gate ring from the center disk and the outer ring.

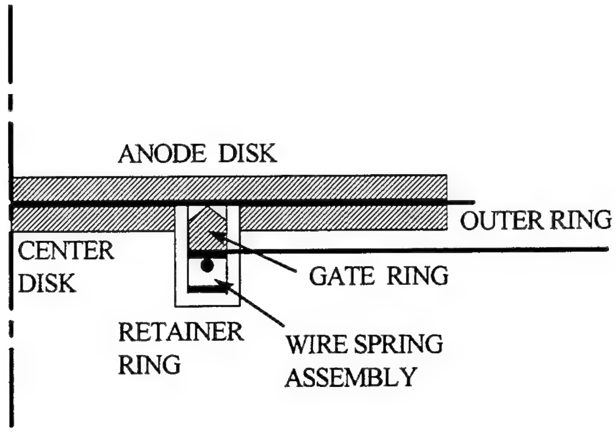

Figure 2. Cross-sectional View of the Molybdenum Parts and the Hatched Areas.

The cathode face of the silicon wafer is exposed (see Figure 3) when the center disk, the gate ring, and the outer ring are removed. The silicon wafer has a total diameter of 91 mm and a thickness of 0.56 mm. The cathode face is divided into two regions by a wide circular trace located about half way between the center and the rim of the wafer. This circular trace makes contact with the gate electrode of the package via the gate ring and the radial pins. The gate structure for this thyristor is marked by the circular trace and the polyamide coating that insulates and covers the areas between the cathodes. The cathodes are an array of thin rectangles with semicircular ends inside and outside the circular trace. Each cathode is bordered by a thin black region that separates it from the gate structure. All the cathodes are located within an 81-mm-diameter circle on the wafer. The anode face of the silicon wafer is silver coated and has no other features.

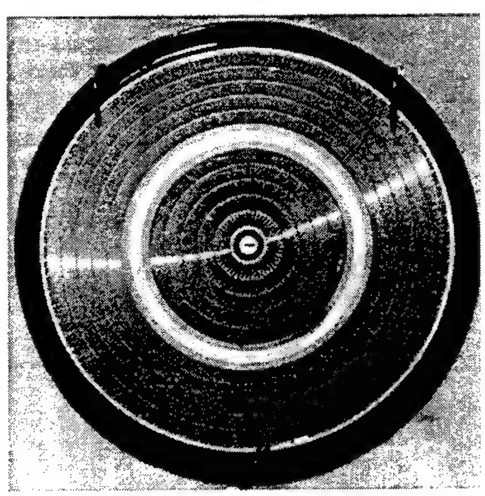

Figure 3. The Cathode Surface of the Wafer, Showing the Gate Structure and Cathode Areas.

3. Trigger Unit

The trigger unit supplied by ABB (see Figure 4) is powered through a contact to the anode of the thyristor. Current to the circuit board is limited by a 350-kΩ resistor string, the seven large resistors on the lower left side of the board, and then voltage regulated to 50 V. A control circuit (the upper left portion of the board) manages the charging of 20 220-μF capacitors in parallel, located just to the left of the thyristor, to about 50 V. Each capacitor is connected to an IFR1010 metal oxide semiconductor field effect transistor (MOSFET) switch made by International Rectifier, which will discharge the capacitor through the gate when it is closed. Once the capacitors are fully charged, the control circuit flashes the "status monitor" light-emitting diode (LED) of a fiber-optic transmitter (second component from the top on the left edge of the board), signaling that the circuit is ready to deliver a current pulse to the gate. When the control circuit receives a light pulse in a fiber-optic receiver (first component from the top on the left edge of the board), the control circuit closes the MOSFET switches to discharge the capacitors through the gate in parallel. The light signal is sent by one of four fiber-optic transmitters in a separate box that is triggered by a single +15-V pulse. Because the use of fiber-optic transmitters and receivers electrically isolates the trigger units from each other, as many as four thyristors can be stacked in parallel or in series and triggered by a single box. Although powering the circuit by the voltage at the anode of the thyristor is convenient, the time for the capacitors to become fully charged depends on the anode voltage. Thus, the time can vary from about 12 seconds for an anode voltage of 4 kV to about 120 seconds for an anode voltage of about 0.5 kV. One can reduce these times by using isolated power supplies for the circuits.

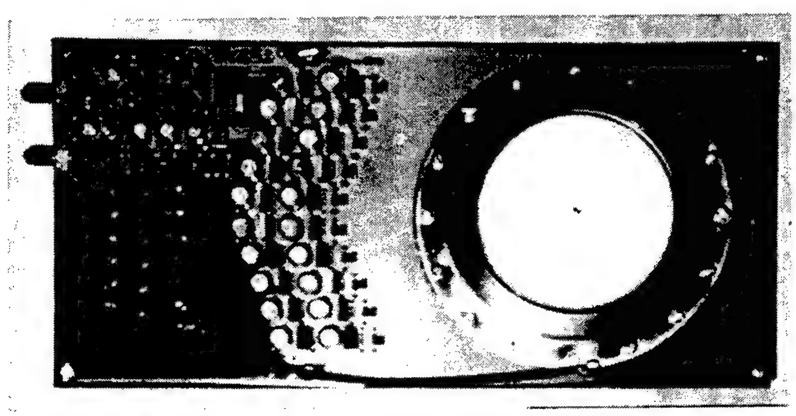

Figure 4. Photograph of the Trigger Unit With a Thyristor.

If the thyristors are operated in parallel or in series, it is important to know if all the trigger units are ready to receive a trigger signal. Serious damage could result

if all the units are triggered when any one of the units is not ready. Thus, a circuit was built that indicates when all the trigger units are ready. The circuit has four fiber-optic receivers that detect when the "status monitor" LED is signaling that its trigger unit is ready by flashing at a rate of 8 to 15 times per second. Each fiber-optic receiver forms an input to a CD4541 "programmable timer". This programmable timer can be configured to generate an output pulse with a width of 1 second when it receives a narrow pulse from the fiber-optic receiver. If the programmable timer receives another pulse within 1 second from the first, the output pulse will be lengthened by 1 second, starting from the last input pulse. Thus, the programmable time will produce a continuous output pulse when input pulses arrive at a rate greater than one per second. A logic circuit turns on an indicator light when all four programmable timers are generating an output pulse. The logic circuit also has four toggle switches that can disable each programmable timer. This allows one to test each trigger unit individually.

We determined the gate current produced by the trigger unit by placing a thin Rogowski coil around the thyristor between the gate electrode and the cathode electrode. A passive circuit integrates the output of the Rogowski coil to produce a signal that is proportional to the current. Figure 5 shows the gate current to the thyristor when the anode and the cathode were shorted together. These results show that the current reaches its maximum of 9.5 kA at 3.5 μs, which includes a time delay of 0.5 μs. Thus, the 10% to 90% rise time for this pulse is about 2.5 μs. This large current pulse with a fast rise time should drive the thyristor to full conduction on the order of the rise time but at the expense of storing 5.5 J of energy in the trigger unit. Figure 6 shows that the voltage across the gate rapidly increases at the beginning of the pulse and drops to about 0.76 V, which is then constant for at least 1.0 ms.

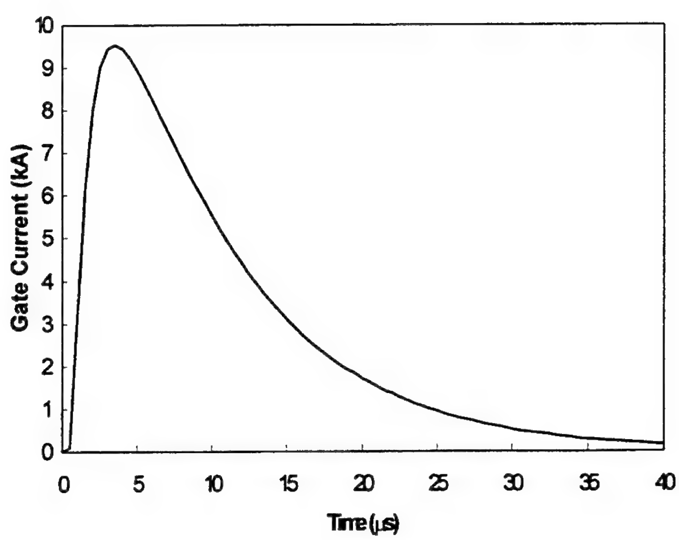

Figure 5. Gate Current Produced by the Trigger Unit.

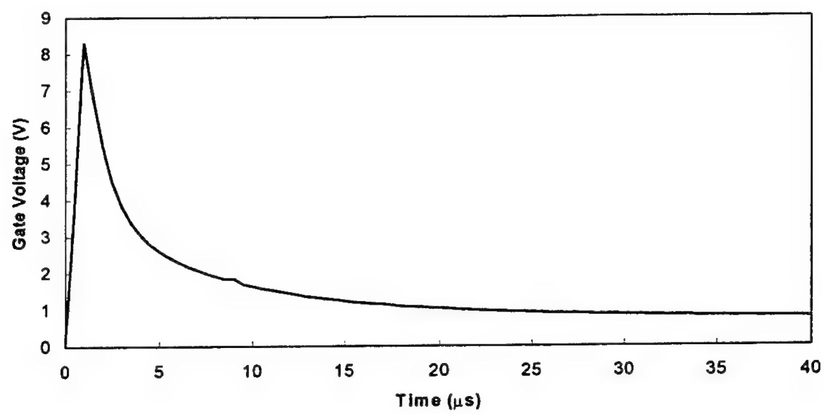

Figure 6. The Gate Voltage.

4. Strip Line Test Stand

A capacitor bank (see Figures 7 and 8) was constructed to test the thyristors with a current pulse that has a maximum value of 150 kA for 50 μs, as specified by the manufacturer. The capacitor bank has three 200-μF capacitors feeding a strip line that connects to the thyristor and a diode in series. The dimensions of the strip line were chosen so that its inductance was approximately 0.5 μH. Because the resistance of this circuit is very low (about 10 mΩ), the current pulse is a slightly damped sine wave with a half period of 55 μs when the current returns to zero and reverses direction. Since these thyristors are of the type that do not block a reverse current, the fast recovery diode in series with the thyristor protects it from this reverse current. The diode is specified so that it can conduct a surge current of 115 kA for 1.0 ms. With this specification, the diode should withstand a surge current of about 500 kA for 50 μs, a pulse that has the same action integral $I^2t/2$ as the specifications, 6.6 kA^2 s.

The diagnostics included in the test stand measure the voltage across the diode or thyristor, the current in the circuit, and the time derivative of the current. Voltages were measured by a high voltage divider that has a bandwidth of 10 MHz, which was made by Ross Engineering Corporation. The current in the circuit was determined from the voltage across a current-viewing resistor (CVR), which has a number of nichrome wires in parallel for a total resistance of 0.76 mΩ. The time derivative of the current dI/dt was measured by a Rogowski belt wrapped around one of the strip line rails. Its data were used to correct for the small contributions of the inductance in the CVR and the diode to their respective voltage measurements.

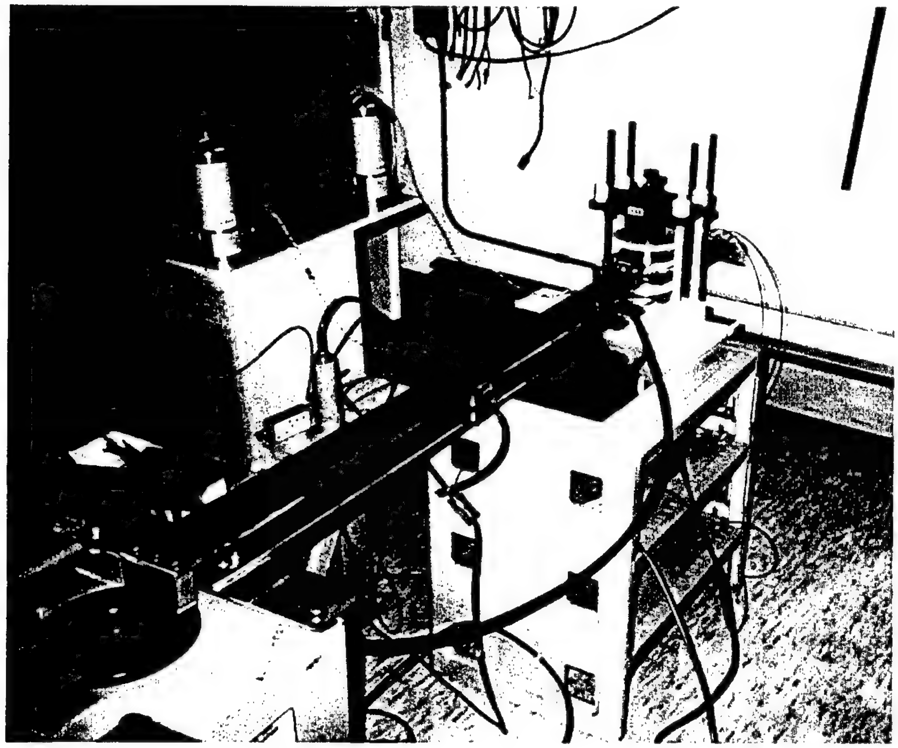

Figure 7. Strip Line Test Stand.

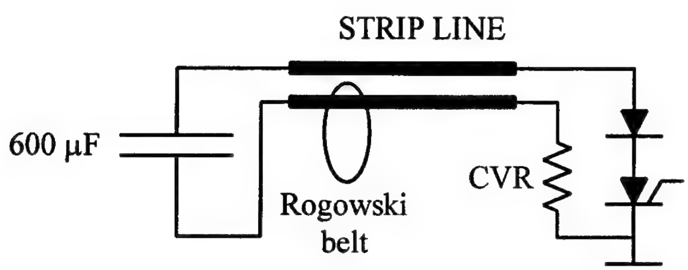

Figure 8. Schematic of the Strip Line Test Stand.

From the literature for the thyristor and the diode, the diode is normally a free wheeling diode that is connected in parallel with the thyristor, but here, the diode is in series with the thyristor to act as a blocking diode. This arrangement permits the voltages across the thyristor or the diode to be measured when the same current is flowing through them.

In the first series of tests, there was no snubbing circuit in parallel with the thyristor/diode stack. The capacitor bank was charged to an initial voltage, and then a trigger pulse was sent to the firing circuit of the thyristor to initiate the capacitor bank current. This was repeated for initial capacitor bank voltages from 0.5 kV to 4.0 kV in 0.5-kV steps. The diode or the thyristor failed when the

capacitor bank was initially charged to 4.0 kV. The currents in this series are shown in Figure 9, and the dI/dt for the currents are shown in Figure 10.

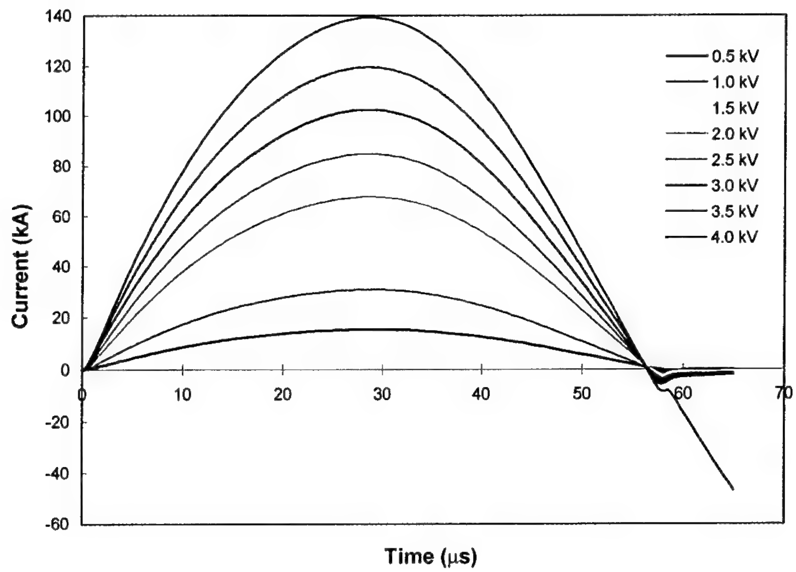

Figure 9. Current Pulses Without a Snubbing Circuit.

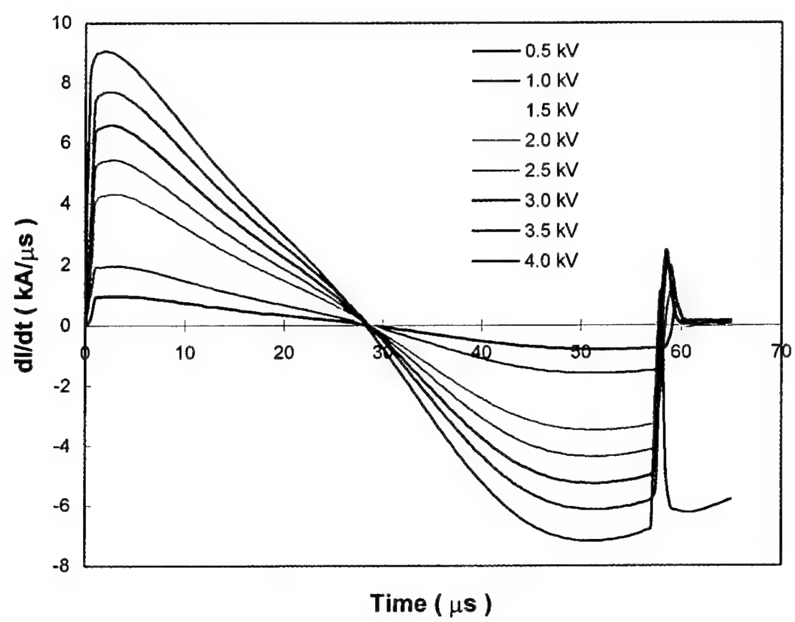

Figure 10. The Time Derivative of the Current Pulses.

It was speculated that the reverse voltage on the diode exceeded its limit of 4.5 kV in the previous test when the capacitor bank had an initial voltage of 3.5 kV. This large reverse voltage was generated from the rapid change of current in the inductance of the circuit, but the total voltage across the diode in Figure 11 shows that the peak reverse voltage on the diode was only about 3.3 kV. Thus, this diode and thyristor did not meet the specifications and the reason for the failure is not known.

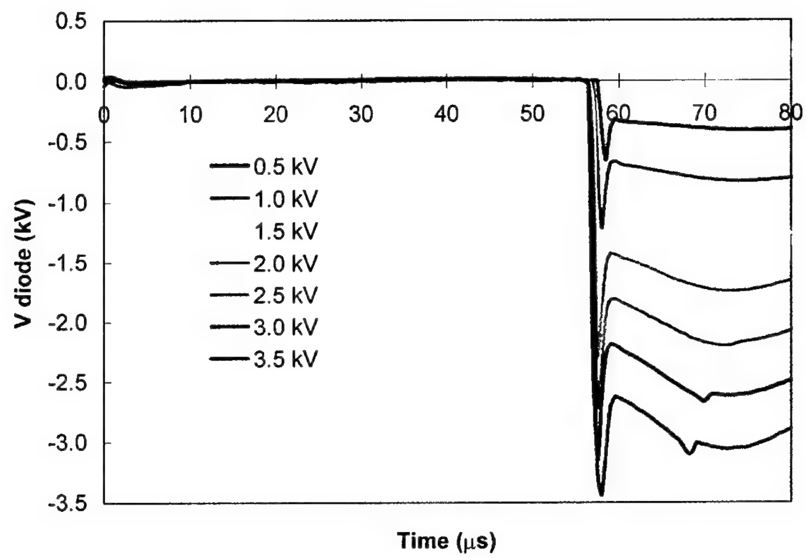

Figure 11. The Reverse Voltage.

A resistor-capacitor snubbing circuit consisting a 0.15-Ω resistor in series with a 100-μF capacitor was installed in parallel to the thyristor and diode. Current pulses for this series of test are consistent with the current pulses shown in Figure 9, except when the current reverses and the current from the snubbing circuit is present. The thyristor and the diode survived a pulse with a peak current of 134 kA and an initial dI/dt of 8.3 kA/μs after the capacitor bank was charged to 4.0 kV; both values are close to the stated limits of 150 kA and > 10.0 kA/μs for the thyristor.

The snubbing circuit was removed for the tests where the voltage drop across the thyristor and the diode were studied. Because the snubbing circuit protected the diode from excessive voltages, the voltage on the capacitor bank was limited to 3.0 kV. The voltage across the diode or thyristor as measured by the high voltage divider has a component attributed to the inductance of the diode. Using the data from the Rogowski belt, it is possible to correct the measured voltage for this component. Figure 12 shows the voltage across the thyristor on a logarithmic scale when the capacitor bank was charged to 2950 V, which generated a peak current of 93 kA at 30 μs. The time for the anode voltage to drop from the charge voltage to less than 10 V is typically 3.0 μs to 5.0 μs, which indicates the time for

the trigger unit to drive the thyristor to full conduction. The broad peak between 5 μs and 55 μs is the voltage drop of the current flowing through a semiconductor. This voltage reached a maximum of about 17 V at about the same time the current reached a peak of 93 kA.

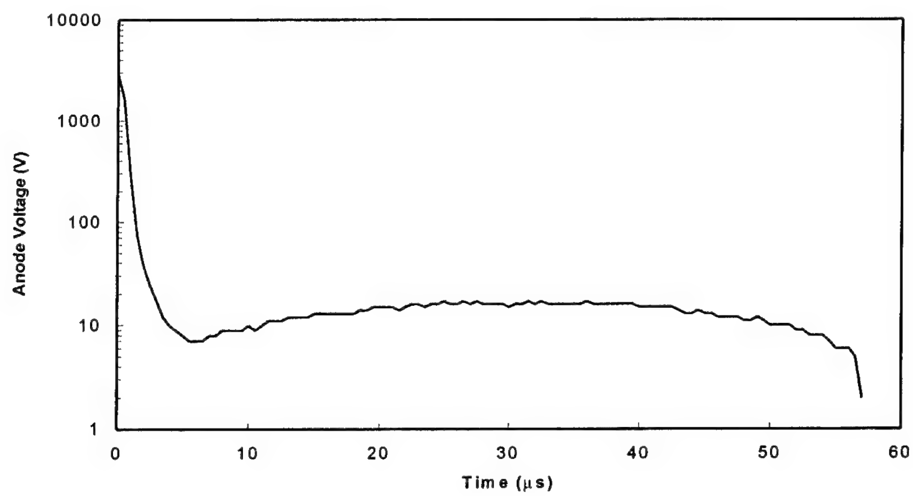

Figure 12. Voltage Drop Across the Thyristor.

To aid in the measurement of the voltage across the diode, the positions of the thyristor and the diode in Figure 8 were exchanged, which placed the cathode of the diode at ground. This type of diode exhibits a forward voltage recovery peak where the voltage across the diode increases as the current also increases. This voltage increases to a maximum and decreases even when the current may still be increasing. Figure 13 shows the forward voltage recovery peak of the diode followed by the voltage drop of the current flowing through the diode for various peak current pulses. A maximum voltage drop of 22 V occurred at 27 μs when the current reached a maximum of 93 kA. Figure 14 shows the peak values of the forward recovery voltage as a function of the initial dI/dt of the current pulse up to 5.6 kA/μs, whereas the ABB specifications are given only to 1.0 kA/μs.

Figure 15 is the portion of the current pulse when the diode is starting to block the current. The capacitor bank was initially charged to 3.0 kV for this example. The minimum current Ir, as marked in Figure 15, is the recovery current of the diode that depends on the dI/dt at the time the current crosses zero. This dependence is shown in Figure 16 where the positive values of the crossing dI/dt and Ir are used. The recovery charge, the integral of all the negative current, is also a function of the zero crossing dI/dt of the current, as shown in Figure 17. The symbols in Figures 16 and 17 are results from four series of tests done on the test stand for different diodes used with different thyristors.

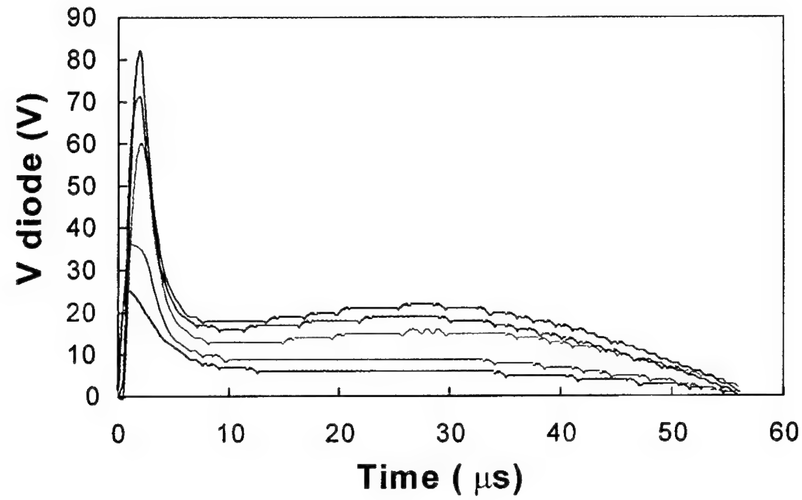

Figure 13. The Forward Voltage Drop Across the Diode.

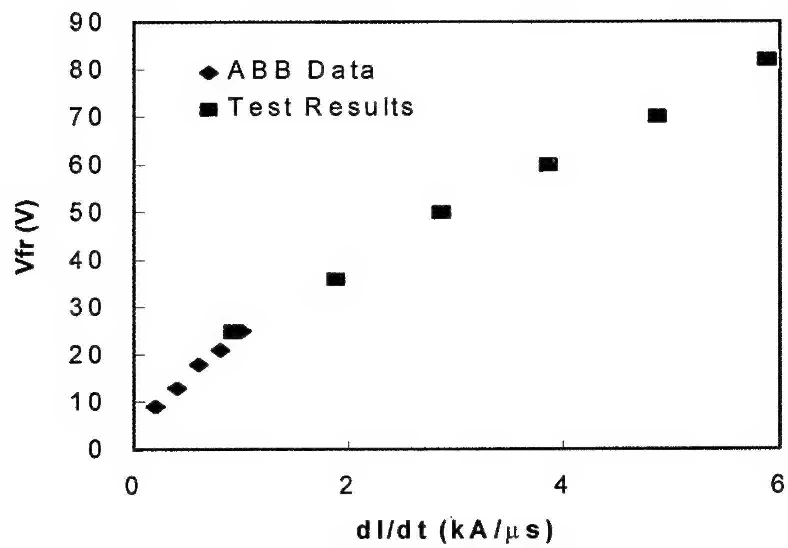

Figure 14. Peak Forward Recovery Voltage Versus the Initial dI/dt of the Current Pulse.

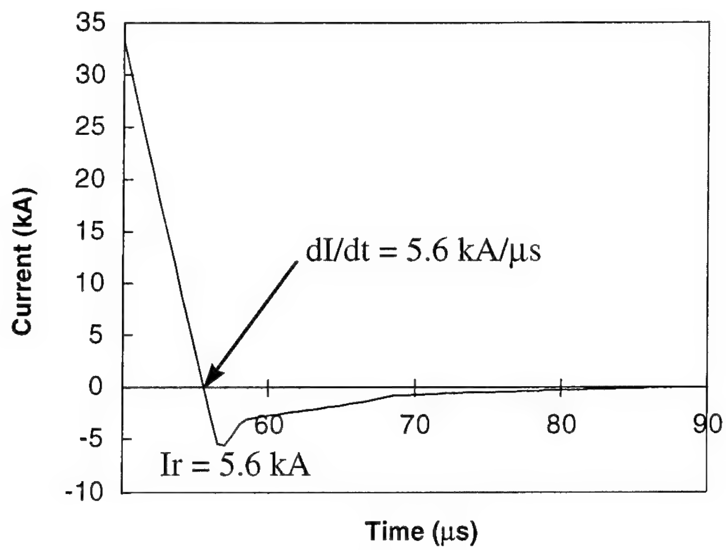

Figure 15. The Recovery Portion of the Current Pulse.

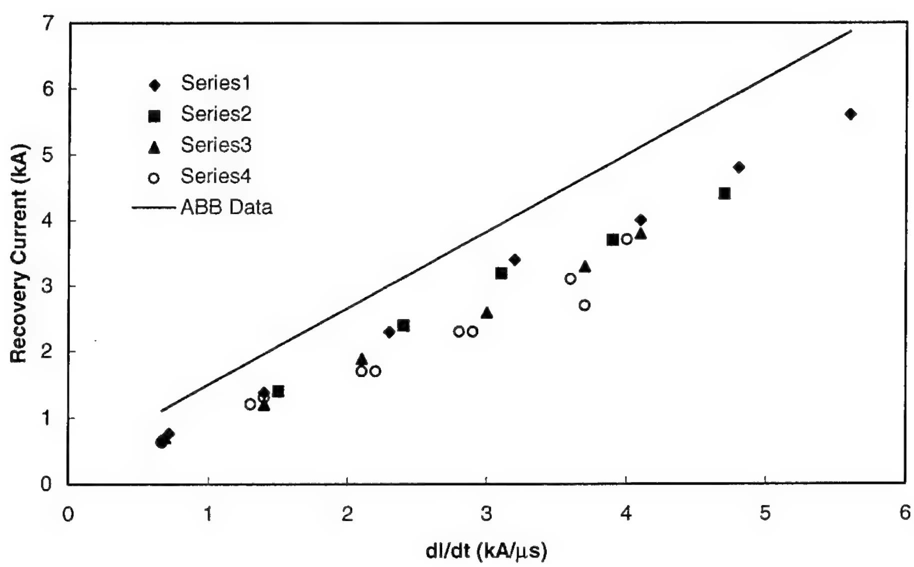

Figure 16. Recovery Current for Different Diodes Used With Different Thyristors.

The solid lines in Figures 16 and 17 are linear extensions of the graphs from ABB specification sheet which only go as high as 1.0 kA/µs. Figure 16 shows that the recovery currents have some variations about a line below that of ABB's specifications. Figure 17 shows that the recovery charges, however, had a wide variation that may be attributable to the different conditions in these tests. The lower recovery currents may reduce the size of the components in the snubbing

circuits, but the wide variations in the recovery charges complicate the design of the snubbing circuits.

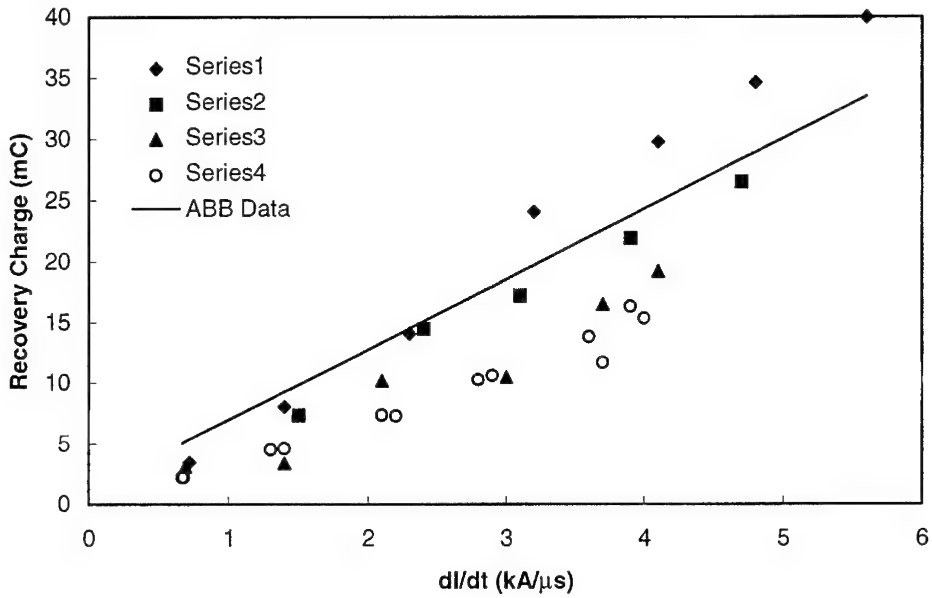

Figure 17. Recovery Charge for Four Test Series.

We determined the maximum stand-off voltage of a thyristor by connecting it to the capacitor bank without a trigger unit and shorting the gate to the cathode. To limit the damage to the thyristor, two of the capacitors were removed and a thin copper wire imbedded in glass beads was connected between the capacitor and the anode of the thyristor. The thin copper wire acted like a fuse and interrupted the current when the thyristor broke down. The voltage on the capacitor bank was monitored by a high voltage probe as the capacitor bank was slowly charged and noted when the thyristor broke down at 5.4 kV. Small pit marks were found on the faces of the cathode area of the wafer and no damage at the edge of the wafer. This indicates that the breakdown occurred across the wafer. This experiment was then performed on a diode. As the capacitor bank was being charged by a 10-mA current, the voltage on the capacitor bank increased at a steady rate until about 5.5 kV and stopped at about 5.6 kV. The current to the capacitor bank was then immediately reduced to zero, and the charge on the capacitor bank was discharged. We evaluated the integrity of the diode by charging the capacitor bank again to about 2.0 kV when the charging supply was disconnected from the capacitor bank by opening a high-voltage relay. The voltage on the capacitor remained steady, which indicated that the diode was drawing very little current. Thus, the diode started to draw current at 5.6 kV and did not fail catastrophically.

Some applications may require a number of thyristors to be operated in series. In this configuration, the thyristors should have an equal voltage across them at all

times: from the time just before they are triggered, during the time that they are turning on, and during the time they are conducting a current. To measure these voltages, three thyristors were stacked in series with a single blocking diode on top of the stack (see Figure 18). The three thyristors should hold the voltage on the capacitor bank when it is charged to three times the voltage rating of a single thyristor (4.5 kV), making a total of 13.5 kV. If the capacitor bank were to be charged to 13.5 kV and then discharged through the stack, the voltage on the capacitor bank would be about –10 kV when the current returns to zero and the diode would then block a reverse voltage of 10 kV. Because the maximum reverse voltage of the diode is only 4.5 kV, the diode would fail in the present capacitor bank configuration. The reverse voltage of the diode at the end of the current pulse can be reduced by adding resistance to the capacitor bank circuit. Thus, the top rail of the strip line from the capacitor bank was replaced by two stainless steel tubes that had thin walls, which added 38 mΩ to the circuit. This added resistance changed the current pulse from a damped sine wave to a near critically damped sine wave (see Figure 19).

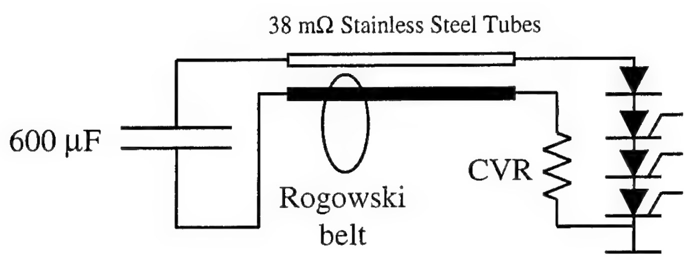

Figure 18. Schematic of a Stack of Three Thyristors and a Diode.

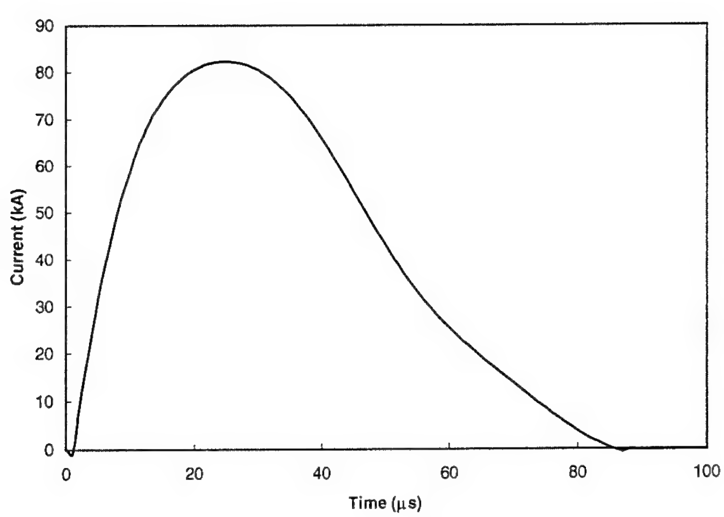

Figure 19. Current Pulse at 6.0 kV.

The voltage across each thyristor is shown in Figure 20 when the capacitor bank was initially charged to 6.0 kV and the current pulse shown in Figure 19 is passed through the stack. The symbols for each thyristor are slightly displaced in time at each microsecond for clarity. The voltage across each thyristor before triggering is simply the voltage drop across each trigger unit and does not depend on any characteristics of the thyristor. The equality of the voltages from 0 μs to 10 μs (see Figure 20) indicates that the thyristors were simultaneously triggered and that the voltages are being shared during the time that the thyristors are being turned on. Unfortunately, noise in the voltage signals prevents a clear demonstration that the voltages are being shared during the current pulse. It could be said, however, that the voltages are within a maximum ±10 V of each other during this time.

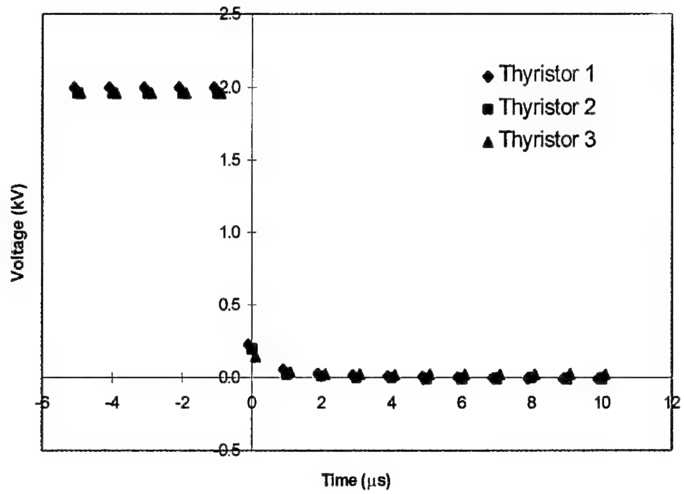

Figure 20. Voltage Across Each Thyristor.

5. Coil Gun Experiments

The thyristor is rated to a 150-kA pulse with a pulse width of 50 μs. If the shape of this pulse is a half period sine wave, the action for this pulse would be only 0.56 kA^2 s and this may not be the maximum action. To determine the maximum action and to demonstrate a use for these thyristors, a thyristor was connected to a coil gun circuit that can produce a current pulse with a large action integral.

This coil gun circuit is an electromagnetic launcher that is well suited for launching conducting plates. In this launcher, a time-varying magnetic induction produced in an external launch coil induces a current in the plate to be launched. The force between the induced current and the external magnetic induction

accelerates the plate out of the coil. High velocities can be achieved by the use of a number of external coils arranged in line along a path. As a plate passes through a coil, a current pulse is delivered at the proper time to accelerate the plate toward the next coil. Because each coil requires a switch, the use of thyristors in this application could reduce the weight of the system and improve the reliability. Thus, a thyristor and a blocking diode were placed in a single-stage coil gun that was built to perform sub-scale experiments (see Figure 21). The capacitor bank consists of 13 637-μF capacitors for a total capacitance of 8.3 mF. The resistor in Figure 21 represents the resistance of the circuit and other energy loss mechanisms that occur when the plate is launched. The launch coil in this case had an inductance of 7 μH when the aluminum plate was positioned for launch and increased to 9 μH when the aluminum plate was removed. Because the time derivative of the current when the current returns to zero was estimated from the circuit parameters to be less than 0.1 kA/μs, the voltage transient across the thyristor and diode was expected to be less than the blocking voltage of the diode without a snubbing circuit. Thus, no snubbing circuit was used.

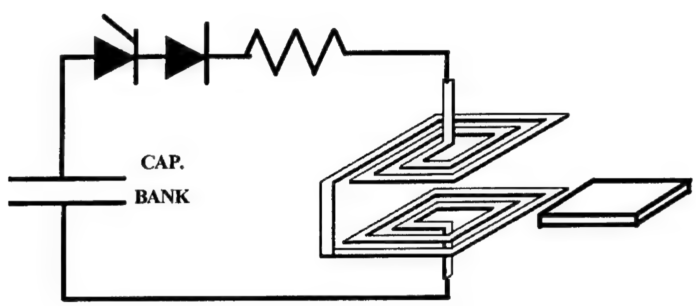

Figure 21. Schematic of a Single-Stage Coil Gun That Uses a Thyristor and a Diode as a Switch.

The total current to the launch coil was measured by a Pearson coil. There was also a high voltage divider that measured the voltage across the launch coil and another high-voltage divider that measured the voltage across the launch coil plus the voltage across the thyristor and diode. The currents in Figure 22 resulted when the capacitor bank was charged to 2.5 kV, 3.0 kV, 3.5 kV, and 4.0 kV, resulting in plate velocities of 60 m/s, 80 m/s, 100 m/s, and 121 m/s, respectively. The velocity of the 470-g plate was calculated from the times the plate crossed two light beams. The current pulses are not proportional to the charge voltage of the capacitor bank because the inductance of the launch coil will vary differently with time for different plate velocities. After the capacitor bank was charged to 3.5 kV, the thyristor and the diode successfully delivered a current pulse with a peak current of 76 kA and an action of 2.7 kA^2s to the load, but they failed when a current pulse with a peak current of 84 kA and an action of 3.4 kA^2s was delivered to the load after the capacitor bank was charged to 4.0 kV.

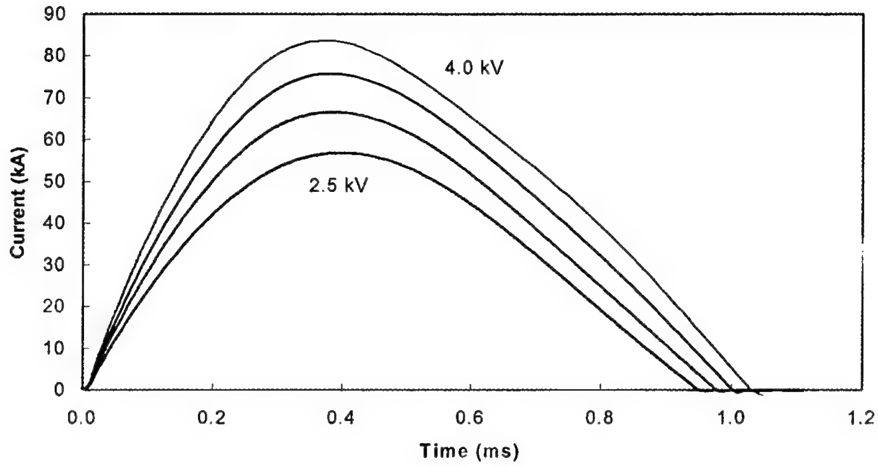

Figure 22. Coil Gun Current.

There is some evidence that the diode was damaged by the 76-kA pulse. This evidence is seen when the recovery voltage across the thyristor and the diode for the 67-kA pulse generated when the capacitor bank was charged to 3.0 kV was compared to the 76-kA pulse generated when the capacitor bank was charged to 3.5 kV. The recovery voltage for the 67-kA pulse (see Figure 23) varied smoothly and had a minimum voltage of -1.87 kV. The recovery voltage for the 76-kA pulse as shown in Figure 24, however, shows rapid voltage oscillations during recovery, which did not exceed the blocking voltage rating of the diode. Although the diode did prevent a reverse voltage, these oscillations may indicate some damage. Thus, the thyristor or the diode failed during an action of 2.7 kA^2s, which is less than the rated action for the diode, namely, 6.6 kA^2s.

A second series of experiments was performed with two diodes in series with the thyristor. Because the diodes were placed in series, the reverse voltage for each diode is half of the total reverse voltage across both diodes. Each diode had a 1.0-μF snubbing capacitor for additional protection from excessive reverse voltages. No plates were launched in this series. In the first experiment, the capacitor bank was charged to 2.0 kV to assess the diagnostics. The capacitor bank was then charged to 3.9 kV for the second experiment. The current pulse for this experiment had an amplitude of 78 kA and a half period of 1.08 ms, which gave an action integral of 3.3 kA^2s. Because there were no high frequency oscillations on the recovery voltage as was observed in Figure 24 in this experiment and because the thyristor withstood 5.0 kV in the next experiment, the diodes and the thyristor were not damaged by the 78-kA pulse. The capacitor bank was charged to 5.0 kV for the third experiment when a current pulse with an amplitude of 99 kA and a half period of 1.06 ms was passed through the stack. The diodes and the thyristor failed from the 5.2-kA^2s action of this pulse, which is less than the action rating of the diodes (6.6 kA^2s for a 1-ms pulse).

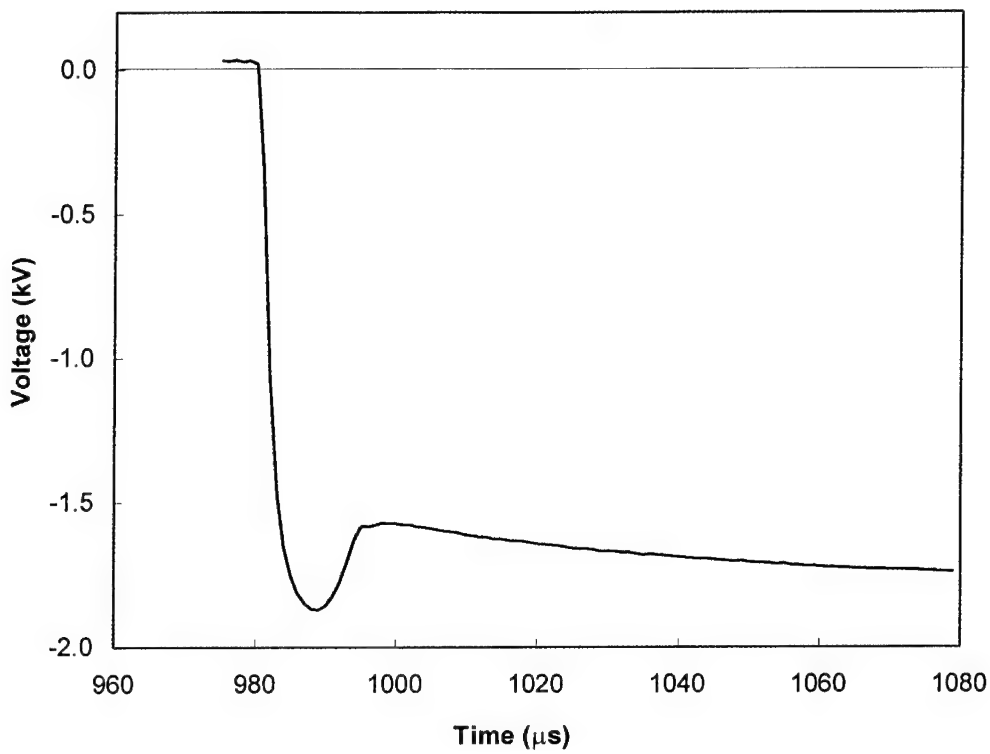

Figure 23. Recovery Voltage for the 67-kA Pulse.

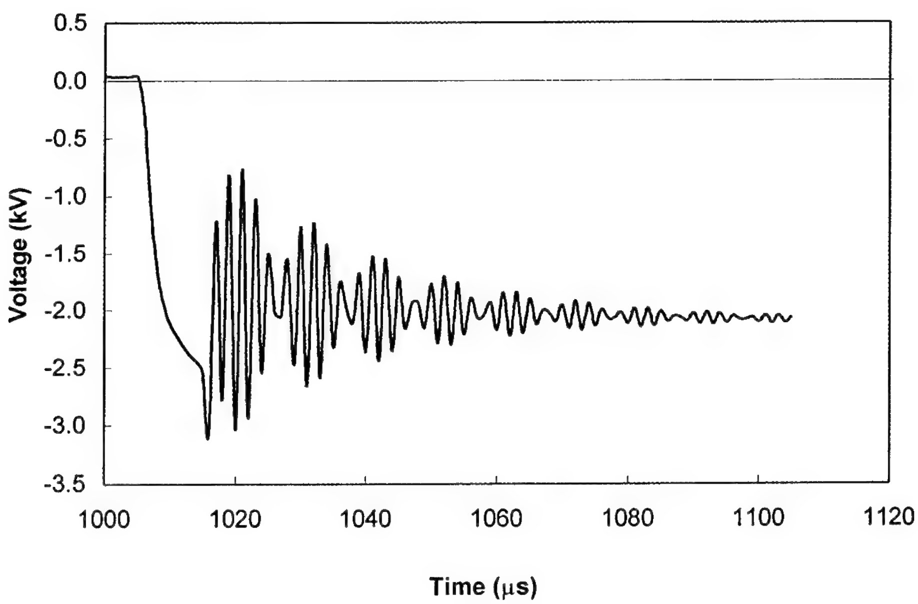

Figure 24. Oscillating Recovery Voltage for the 76-kA Pulse, Which May Indicate Damage.

There are two ways that the thyristor and the diodes could have failed during this last experiment. First, the thyristor could have failed before the diodes

during the half period of the current pulse. Since the action on the diodes does not depend on the integrity of the thyristor after the current starts, the action rating of the thyristor could be less than 5.2 kA^2s. Second, the diodes could have failed, and the thyristor would have then been destroyed by the unblocked current. Thus, the action rating of the diodes could be less than 5.2 kA^2s, but the action of the thyristor could be greater than 5.2 kA^2s. This is unlikely because the action rating of a thyristor should be less than that of a diode of the same diameter. In these diodes, the conducting area is 83% of the total area of the silicon wafer. Since some of the area of the wafer is occupied by the gate structure of the thyristor, the conducting area of the thyristor is less than 83%. Having a smaller conducting area, the current density in the thyristor would be larger than that of the diode when both devices are conducting the same current. This higher current density in the thyristor increases the heating of the wafer and thus reduces its action rating. Therefore, the action rating for the thyristor and the diode is greater than 3.3 kA^2s but less than 5.2 kA^2s.

When the trigger unit was examined after the final experiment, it was found that the heat from the resistors in the resistor chain (the seven 50-kΩ resistors in series) had melted their solder pads and some of them had fallen. Each resistor was dissipating about 10 W when the anode of the thyristor was at 5.0 kV. Although the resistors were rated for 10 W, they were hot enough to melt the solder at the end of their leads. If the resistors had fallen the wrong way, a high voltage could have been applied to the circuit of the trigger unit and could have destroyed it. A more dangerous possibility could occur if a number of thyristors were stacked in series in which the voltage across each thyristor depends on the integrity of the resistor chains in their trigger units. If one of the resistors had melted the solder and slipped off the pad to break the resistor chain, the voltage across the thyristor could have exceeded its maximum and failed, followed by a failure of the other thyristors in the stack. This problem could be avoided by replacing the seven 50-kΩ resistors with 100-kΩ resistors that are rated for 10 W. Doubling the resistance of the resistor chain will increase the time for the trigger unit to be charged and be ready to be triggered. If the operating voltage is greater than 3.0 kV, this increase in the waiting time should not be an inconvenience. If the operating voltage is less than 3.0 kV, then there is no need to replace the 50-kΩ resistors.

6. Summary

There are notable differences between these experimental results and the specifications of the fast recovery diode, 5SDF 16L4502. First, the maximum action for the diode was specified as 6.6 kA^2s for a 1.0-ms wide current pulse, while the coil gun experiments show that the diodes failed with an action of only 5.2 kA^2s. Second, the experiments found that the recovery currents of the diode

were less than the specifications, and the recovery charges were closer to the specifications but with wide variations. These experiments have measured these quantities and the peak forward recovery voltage when the crossing dI/dt was greater than the specification's 1.0 kA/μs. These data will be important in designing snubbing circuits for the diode, even though the specifications state that the diode is "optimized to use in snubberless operation". Finally, an experiment showed that the maximum reverse voltage of the diode was 5.6 kV, and the diode did not fail catastrophically at this voltage but started to conduct a large reverse current. The specifications for the thyristor 5SPY 36L4502 did not state the turn-on time, the forward voltage drop, or the maximum action integral. These experiments demonstrated a turn-on time of about 3.0 μs, a forward voltage drop of about 22 V at 93 kA, as shown in Figure 12, and a maximum action integral between 3.3 kA^2s and 5.2 kA^2s. These results and others are presented with ABB specifications in Table 1 for the diode and Table 2 for the thyristor. The quantities that are marked with an asterisk in these tables resulted in the failure of the diode or the thyristor. The other quantity associated with the ones marked with an asterisk is the maximum quantity in these experiments that did not destroy the device.

Table 1. 5SDF 16L4502 Fast Recovery Diode

Parameter	Experimental Results	ABB Specifications
Action for 1-ms pulse	3.3 kA^2 s – 5.2 kA^2 s*	6.6 kA^2 s
Reverse Voltage	5.6 kV	4.5 kV

Table 2. 5SPY 36L4502 High Current Thyristor

Parameter	Experimental Results	ABB Specifications
Action for 1-ms pulse	3.3 kA^2 s – 5.2 kA^2 s*	Not given
Peak Current (50 μs)	134 kA	150 kA
Peak Current (1.1 ms)	78 kA – 99 kA*	Not given
Current Rise Time	8.3 kA/μs	>10.0 kA/μs
Blocking Voltage	5.4 kV	4.5 kV
Voltage drop @ 93 kA	17 V	Not given
Turn-on Time	2.5 μs	Not given
Peak Gate Current	9.5 kA	Not given

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13. ABSTRACT *(Maximum 200 words)*

The semiconductor switch 5SPY 36L4502 manufactured by ABB has the capability of conducting current pulses with an amplitude of 150 kA and a width of 50 ms. This capability was achieved by a silicon wafer that is 91 mm in diameter. In addition, this switch can withstand a current pulse that is initially increasing at a rate of 10 kA/ms. This capability was achieved by a special triggering unit that produces a 9.5-kA pulse with a rise time of 2.5 ms, a low inductance structure between the triggering unit and the internal contact to the gate structure on the silicon wafer, and a highly inter-digitated gate structure. These capabilities make it possible to replace some spark-gap switches, thyratrons, or ignitrons used in research at the U.S. Army Research Laboratory with this semiconductor switch that is smaller, more reliable, and has a longer life time. Because of the possible uses for this switch, its characteristics were evaluated and the requirements for its use were determined. This study should assist in the design of new circuits and should determine if this switch could replace existing switches.

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